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# Advanced Evaluation of Asphalt Mortar for Induction Healing Purposes

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## ABSTRACT

Induction heating technique is an innovative asphalt pavement maintenance method that is applied to inductive asphalt concrete mixes in order to prevent the formation of macro-cracks by increasing locally the temperature of asphalt. The development of asphalt mixes with improved electrical and thermal properties is crucial in terms of producing induction healed mixes. This paper studies the induction healing capacity of asphalt mixes without aggregates as the part of asphalt concrete where inductive particles are dispersed notably contributing to the final response of asphalt pavements. Special attention was given to the characterization of inductive asphalt mixes using experimental techniques and numerical methods. The research reported in this paper is divided into two parts. In the first part, the impact of iron powder as filler-sized inductive particle on the rheological performance of asphalt-filler systems was studied. The mechanical response, the induction heating and healing capacity of asphalt mortar by adding iron powder and steel fibers was evaluated as well. In the second part, the utilization of advanced finite-element analyses for the assessment of the induction heating potential of inductive asphalt mortar with steel fibers are presented. The influential factors of induction mechanism in asphalt mixes are also described. The experimental and numerical findings of this research provided an optimization method for the design of induction healed asphalt concrete mixes and the development of necessary equipment that will enable the implementation of induction technology for healing of asphalt concrete mixes.

## 1. Introduction

Asphalt concrete mixes are the most common types of pavement surface materials applied in transportation infrastructure and consist of asphalt binder, aggregate particles and air voids. These mixes are temperature-dependent materials with a self-healing capability because they can restore stiffness and strength (1-5). Nowadays, it is known that asphalt concrete mixes should be considered as mixes of mortar-coated aggregates rather than binder-coated aggregates in terms of developing asphalt pavements with enhanced durability. In 2014, the European asphalt industry (EU27) produced about 280 million tonnes of asphalt and invested about €80 billion per year in pavement construction resulting increased energy consumption and CO<sub>2</sub> emissions during various asphalt production, construction and maintenance processes (6). The importance of reducing CO<sub>2</sub> emissions by developing new, last longer asphalt mixes and to enhance road safety by providing high quality road network is crucial for fulfilling the European objective for sustainable development. Within this framework, the necessity of solving construction and rehabilitation issues of pavement structures has led industry to focus on development of alternative novel state-of-the-art techniques. Regarding asphalt pavement maintenance, among others (7, 8) healing of asphalt micro-cracks using the induction technique has been approved as a very promising method to prolong the service life of asphalt pavements (9-13).

The induction heating technique has been used as a maintenance technique for asphalt pavements in order to speed up the healing process of asphalt. Field trials are available and a very exciting example is the Dutch motorway A58 near Vlissingen (14). This technique requires new mixes with inductive particles in order

52 to make them suitable for induction heating. Specifically, when an alternating electric current is applied to an  
53 induction coil, a time-variable magnetic field is generated around the coil. According to Faraday's law, this  
54 magnetic field induces currents (eddy currents) in inductive particles within the mix and they are heated up  
55 based on the principles of Joule's law. The generated heat in particles increases locally the temperature of  
56 asphalt mix around the stone aggregates, rather than heating them. Through the temperature rise the  
57 bitumen is melting the micro-cracks are closed and the mechanical properties are recovered (4). This  
58 mechanism of healing asphalt mixes with the assistance of electro-magnetic induction is known as induction  
59 healing.

60 Previous research indicated that asphalt mixes with inductive particles, such as steel fibers, can be heated  
61 in a very short time by using the induction technology (9-17). However, the distribution of steel fibers within  
62 mixes appears to have a direct relation with the volumetric and mechanical properties of asphalt mixes (18-  
63 21). Also, it was observed that the characteristics of steel fibers – diameter and length - are affected by the  
64 mixing and compaction processes (16). Especially, the longer steel fibers easily produce clusters inside the  
65 asphalt mixes, causing inhomogeneity and reducing the mechanical response (15, 16). Apart from the  
66 performance degradation, the large amounts of fiber-type particles cause a significant increase of costs (28).  
67 For this reason and in order to resolve the problems resulted by the fiber-type particles, inductive asphalt  
68 concrete mixes can be produced by adding other types of inductive components.

69 In particular, the effective properties of asphalt mixes vary considerably according to the type and the  
70 characteristics of inductive particles. Higher electrical or thermal conductivity of particles results in higher  
71 effective conductivities of the asphalt concrete mixes. These particles are normally divided into categories  
72 according to their size and shape as: filler-sized (e.g., graphite, carbon black) (11, 32-36), stone-sized (e.g.,  
73 steel slag) (31) and fiber particles (e.g., steel and carbon fibers) (11, 36, 37). Among all the fillers used in  
74 inductive asphalt mixes, carbon black and graphite powder are the most often investigated because of their  
75 excellent associated compatibility with asphalt binder imparting in parallel easy mixing. However, no extended  
76 research has focused on other types of filler-sized inductive particles and for this reason is presumed very  
77 important to develop inductive mixes with well dispersed inductive components to provide sufficient isotropic  
78 material properties to mixes for induction applications.

79 Additionally, more data is still required to clarify the role and the significance of the various parameters on  
80 the asphalt induction heating phenomenon. Induction heating is a complex phenomenon that combines the  
81 electromagnetic and heat transfer theory and has a strong relationship with the electro-thermal properties of  
82 materials (22-24). Furthermore, it is known that the efficiency of the induction heating depends on the  
83 coupling between the size of the inductive particles and the operational characteristics of the induction coil  
84 (frequency, power, shape of the induction coil, etc.). Thus, the experimental and the numerical analysis of  
85 electro-thermo-mechanical properties of asphalt mixes is becoming very important in terms of determining the  
86 most crucial material parameters for obtaining enhanced durability simultaneously with high induction heating  
87 rate.

88 This paper is divided into two investigation approaches; the experimental and the numerical. Since asphalt  
89 mortar is the crucial part of asphalt concrete that suffers more damage and contains the particles for induction  
90 heating, an experimental approach was developed for the sufficient characterization of structural and non-  
91 structural performance of induction heated mortars. The current numerical study provides us this efficient tool  
92 to conduct analysis of induction heating predicting in parallel the heating time needed in order to heal micro-  
93 cracks inside the asphalt mixes.

## 94 95 **2. Experimental Approach**

96  
97 During the induction heating, the asphaltic part around the stone aggregates with the inductive particles is  
98 heated locally resulting durability improvement of the bonding characteristics between asphalt constituents. In  
99 this study focus was given on conducting in-depth analyses of the interaction between the inductive particles  
100 with the other asphalt constituents. Also the evaluation of structural and non-structural performance of  
101 asphalt mastics (binder and filler-sized particles) and mortars (binder, filler-sized particles and sand) was  
102 ascertained crucial.

103 Iron powder was selected as filler-sized particle and its interaction with the other components was studied  
104 on asphalt mastic level. For a certain asphalt binder, asphalt mastics with different volumetric properties were  
105 developed and characterized following an experimental protocol designed for this purpose. It is well  
106 recognized that the performance of asphalt mastic is associated with reinforcement of filler-sized particles in  
107 asphalt mastic (38-40). The particle size of filler, the loading time, temperature and the interaction of fillers  
108 within the binder matrix are the most influential factors for the stiffening of mastics. Rheological and micro-  
109 morphological analyses were carried out quantifying thus the stiffening potential of iron powder with different  
110 contents. The electro-thermal properties were assessed within an effort to obtain the optimal combination of  
111 fillers in this study.

112 After the completion of mastic characterization, sand and steel fibers were added in asphalt-filler systems  
113 in order to prepare the inductive asphalt mortars. The effect of different volumes of fibers and powder on the  
114 electrical conductivity of mortar was evaluated by using the same experimental technique with the mastic  
115 level of analysis. Once the optimal inductive particles combination was obtained, the thermal conductivity of  
116 inductive asphalt mortars was studied. Due to the fact that the improved macroscopic response of asphalt  
117 pavements has a direct link with the durability of asphalt mixes, the mechanical performance of asphalt  
118 mortars were investigated as well. Although the reinforcing impact of steel fibers on mechanical properties of  
119 asphalt mixes has been studied extensively, still limited research was done to evaluate the performance of  
120 asphalt mortars with different inductive particles. At the end of the experimental analysis of this paper, the  
121 induction heating and healing capacity of inductive asphalt mortars were examined.

## 122 123 *2.1 Material and preparation* 124

125 Firstly, the selected mineral fillers and the iron powder as filler-sized inductive particle were analyzed. A  
126 scanning electron microscope (SEM), BET (Brunauer, Emmett and Teller theory) and a Ultrapycnometer have  
127 been utilized in order to determine shape, specific surface area and density, respectively. **Fig. 1** shows the  
128 SEM images of the filler-sized particles; weak limestone (WL) filler, produced limestone (PL) filler and iron  
129 powder (IP). It can be seen that the angular shape and the size of filler limestone – WL and PL – is similar  
130 compared with iron powder (IP) where it has slightly smaller size and smoother surface texture than the  
131 minerals.

132 In order to investigate the impact of iron powder as filler-sized particle within the asphalt mastic, two  
133 asphalt-filler preparation processes were used. The first one was by adding iron powder with replacing an  
134 equivalent volumetric amount of mineral fillers and the other one was without replacing the mineral fillers. It is  
135 important to note that the addition order of fillers, the mixing time and the mixing temperature affect the  
136 dispersion, the segregation and probably the agglomeration of fillers in the mastics. In order to avoid the  
137 settlement of iron powder due to its high density, a preliminary mixing processing analysis was conducted  
138 using a X-ray nano-CT scanner. It was concluded that the lowest air void content and iron powder settlement  
139 was seen when the mixing sequence was the following; (1) addition and mixing of filler-sized particles  
140 together for 90 sec and (2) addition of asphalt binder which is SBS polymer modified and mixing it together  
141 with particles for 120 sec. Mixing was carried out at 180 °C. The compositions of the different inductive  
142 asphalt mastics (F().P()) are given in Table 1. The notation F indicates mineral filler and P represents iron  
143 powder. The values in the brackets indicate the corresponding volume of the components.

144 After the performance evaluation of asphalt mastics, inductive asphalt mortar was developed. The weight  
145 percentage of components in the original asphalt mortar was 33%, 5%, 34% and 28 % for mineral filler WL,  
146 PR, sand and asphalt binder, respectively. For the development of asphalt mortar, steel fibers (SF) (7756  
147 kg/m<sup>3</sup>, initial length 2.5 mm and diameter 0.083 mm) were mixed with the other components as volume  
148 percentage of asphalt binder. Also, in this level of study, the inductive mortars were prepared with different  
149 volume percentages of iron powder added after substituting the equivalent volumetric part of mineral fillers in  
150 order to avoid volumetric degradation. The final optimal amount of iron powder in asphalt mortar was  
151 determined from the electrical conductivity measurements. This specific amount was used for the further  
152 experimental investigations. Initially, different combinations of steel fibers were mixed to obtain the

153 percolation threshold. Later, iron powder of 5%, 10%, 15%, 20% and 25% was added and the amount of  
 154 steel fiber by volume of bitumen was kept constant (4%).

155

## 156 *2.2 SEM Imaging*

157

158 Micrographs of the inductive asphalt mastics were captured using a scanning electron microscope (SEM).  
 159 The micrographs were obtained from a JEOL JSMM 6500F using an electron beam energy of 15 keV and  
 160 beam current of approx. 100 pA. The backscattered electron image mode (BSE) was selected for the image  
 161 acquisition. Aluminum cylinders with a height of 18 mm and a diameter of 31 mm were used as sample-  
 162 substrates for SEM scanning. A thin film of mastic was applied on a glass plate at 140 °C in order to form a  
 163 very smooth area at one side after which the sample was stored at room temperature for 24 hours. Then, the  
 164 sample was gently cut and placed on the aluminum cylinders. The study of micro-morphology of asphalt  
 165 mastic was performed in environmental mode.

166

## 167 *2.3 Frequency sweep test*

168

169 Dynamic shear rheometer (DSR) was utilized to obtain the rheological properties of the inductive asphalt  
 170 mastic. Frequency sweep tests were carried out over a temperature range of -10 °C to 60 °C and the complex  
 171 modulus and phase angle were determined. By shifting these mechanical properties to a reference  
 172 temperature (i.e. 30 °C), the master curves of the complex modulus and phase angle were built up for all  
 173 inductive mastics. Before starting frequency sweep tests, a stress sweep test was conducted in order to  
 174 identify the material linear viscoelastic range (LVR). The LVR is characterized as the 10% stiffness reduction  
 175 criterion and was used to filter the linear and non-linear viscoelastic region.

176

## 177 *2.4 Determination of electro-thermal properties*

178

179 After the preparation of the inductive asphalt mixes, the material was poured in silicon-rubber mould, to  
 180 obtain samples with rectangular dimensions 125 × 20 × 25 mm. The electrical resistivity measurements were  
 181 done by performing the two-electrode method at a room temperature of 20 °C. In order to avoid the problem  
 182 of binder concentration at the surface of contact area and to achieve sufficient and low resistance contact  
 183 with the electrodes, the short ends of specimen are cut by 1mm and a very thin silver paste was glued at both  
 184 ends. The electrodes were made of copper, placed at both sides and the electrical volumetric resistance was  
 185 measured using a digital multimeter. In the experimental measurements, the electric field and the contact  
 186 resistance between the electrodes and the mix was considered constant and zero respectively.

187 The geometry and the electrical resistivity of the inductive asphalt mastic and mortar are the only  
 188 parameters that influence the electrical resistance. The difference in potential value between the electrodes  
 189 and their total charge do not play a role for this material property. Therefore, the electrical resistivity was  
 190 obtained from the second Ohm's law as follows:

191

$$\rho = \frac{RS}{L} \quad (1)$$

192

193 where  $\rho$  is the electrical resistivity, measured in  $\Omega\text{mm}$ ,  $L$  is the internal electrode distance, measured in mm,  
 194  $S$  is the electrode conductive area measured in  $\text{mm}^2$  and  $R$  is the measured resistance, in  $\Omega$ .

195 Thermal conductivity measurements were performed by using the C-Therm TCi thermal analyzer, **Fig. 2**.  
 196 The thermal sensor was working according to the Modified Transient Plane Source Method to determine the  
 197 thermal resistivity of asphalt mixes. The material was poured in a conical-shaped mould with height of 15 mm  
 198 and top and bottom diameter of 50 mm and 55 mm, respectively. The sensor was heated by a small current  
 199 and the response was monitoring while in contact with the specimen. The thermal resistivity of the specimen

200 were measured and obtained directly from the sensor. From the inverse of the resistivity the conductivity is  
 201 defined as:  
 202

$$q = -k \cdot \frac{dT}{dx} \quad (2)$$

203 where  $q$  is the heat flux (the amount of thermal energy flowing through a unit area per unit time),  $dT/dx$  is the  
 204 temperature gradient and  $k$  is the coefficient of thermal conductivity, often called thermal conductivity. The  
 205 heating, reading and cooling process was repeated 6 times per specimen to obtain an average of the  
 206 reading. For both electrical and thermal measurement, three replicas were used.  
 207  
 208

### 209 *2.5 Mechanical performance*

210  
 211 In order to investigate the impact of inductive particles on the mechanical properties of the asphalt mortar,  
 212 direct monotonic tensile tests were carried out. A 25 kN electro-hydraulic servo testing machine was used  
 213 and the monotonic tension tests with freely rotating hinges were performed on specimen from inductive  
 214 asphalt mortar. In order to reduce undesired eccentricities, the specimen were carefully positioned in the  
 215 special designed steel hinges. Furthermore, the inductive asphalt mortar specimen had a parabolic geometry,  
 216 **Fig. 3**, with height of 34 mm for the parabolic part and a thickness of 10 mm in the middle. The monotonic  
 217 tension tests were performed at different displacement rates. The fatigue performance was tested in load  
 218 control mode. All tests were carried out at a constant temperature of  $-10\text{ }^{\circ}\text{C}$ .  
 219

### 220 *2.6 Induction heating*

221  
 222 The induction heating experiment was performed with a 550 V RF generator 50/100 (Huttinger Electronic,  
 223 Germany), see **Fig. 4**, at a maximum frequency of 63.5 kHz. The distance from the mortar sample ( $125 \times 20$   
 224  $\times 25$  mm) to the coil was 10 mm and the data were obtained from the surface of the specimen by using an  
 225 infrared (IR) thermometer.  
 226

### 227 *2.7 Induction healing*

228  
 229 In order to determine the healing efficiency of asphalt mortar after mixing inductive particles, asphalt mortar  
 230 beams were produced with dimensions  $105 \times 25 \times 13$  mm in a mould with a notch at the middle. A similar  
 231 experimental procedure as proposed by Liu et al (12) was selected to test the healing capacity of the asphalt  
 232 mortar. The sample was placed in a chamber at  $-10\text{ }^{\circ}\text{C}$  and was broken into two pieces using the three point  
 233 bending setup. The two pieces were then placed back into the mould. At the final stage, the two pieces were  
 234 heated via induction energy until the surface temperature reached  $120\text{ }^{\circ}\text{C}$ . This process was continued after  
 235 resting the sample for 2 hours at  $20\text{ }^{\circ}\text{C}$ . Moreover, this process was repeated until the damage was too high  
 236 to continue the healing process (12). Concerning the temperature,  $-10\text{ }^{\circ}\text{C}$  was chosen in order to avoid  
 237 permanent deformation of the material and to obtain a brittle fractured surface. For the induction healing  
 238 analysis, 5 samples were used for each type of inductive mortar.  
 239

240 The induction healing performance was evaluated by using the relation given below:

$$S(t) = \frac{F_i}{F_0} \quad (3)$$

241 where  $F_0$  is the fracture force of the sample during a three point bending test, and  $F_i$  is the fracture force after  
 242 the induction heating.  
 243  
 244

## 245 **3. Numerical Approach**

246  
247 As previously described, inductive particles are required into the asphalt mixes in order to make them suitable  
248 for induction heating. Addition of inductive fibers is much more effective than to add inductive filler-sized  
249 particles (11) and also the volume of these and binder influences the induction heating efficiency (13). Also, it  
250 has been observed that the thermal and the electrical conductivity as well as the induction heating efficiency  
251 are dependent of the volume of fibers in asphalt mixes (15). Consequently, apart from the operational  
252 conditions – frequency, intensity of the magnetic field, etc - the efficiency of this type of electromagnetic  
253 heating is dependent on the effective properties of the asphalt mixes with inductive fibers and other particles.

254 However, still limited research was conducted to quantify the influence of different operational parameters  
255 of an induction system on heating efficiency of asphalt mixes. The second part of this paper studies the  
256 important factors of induction heating in asphalt mortar mixes. The 3D finite element meshes of asphalt  
257 mortars with different volumes of steel fibers were generated using X-ray scans in order to evaluate the  
258 effective electrical and thermal properties. After the numerical determination of important induction  
259 parameters for the inductive asphalt mortar, a 3D finite element model of electromagnetic phenomena  
260 coupled with heat transfer physics was developed.

### 261 262 *3.1 Finite element meshes of asphalt mortar*

263  
264 Previous researches (13, 15) indicated that, by adding inductive particles (e.g., steel fibers), an asphalt mix  
265 can be heated up in a very short time by using the induction technology. In order to simulate the effective  
266 electrical and thermal properties of inductive asphalt mixes, the 3D finite element meshes of inductive asphalt  
267 mortars - as a representative of the asphalt mixes without stone aggregates - with different volumes of steel  
268 fibers were generated by using High-resolution X-ray CT (Computed Tomography) images.

269 The High-resolution X-ray CT is a completely non-destructive technique for visualizing features in the  
270 interior of opaque solid objects, and for obtaining digital information on their 3D geometries and properties.  
271 By the X-ray CT technology, the different densities of individual components (e.g., sand, filler, air voids and  
272 bitumen) in the asphalt mortar can be distinguished by the gray levels in a CT slice.

273 Simpleware software (27) was utilized to comprehensively process 3D image data and to generate volume  
274 and surface meshes from the image data. Meshes can be directly imported into the COMSOL multiphysics  
275 finite element software for the electrical and thermal conductivity analyses. The process of reconstruction of  
276 3D images of inductive asphalt mortars is illustrated in **Fig. 5**.

### 277 278 *3.2 Finite element models and parameters*

279  
280 A finite element model predefined in the COMSOL software (25, 26), which can simulate electro-magneto-  
281 thermal phenomena in a real time system, has been utilized for modelling induction heating in the asphalt  
282 mortar. The electromagnetic field was modeled by means of the magnetic field intensity vector  $\mathbf{A}$  [ $A/m^2$ ] and  
283 the magnetic flux density vector  $\mathbf{B}$  [ $A/m$ ] as shown in equation 4:

$$(j\omega\sigma - \omega^2\epsilon_0\epsilon_r)\mathbf{A} + \nabla \times \left( \frac{1}{\mu_0\mu_r} \mathbf{B} \right) - \sigma \mathbf{v} \times \mathbf{B} = \mathbf{J}_\varphi^e \quad (4)$$

285  
286 where  $j$  denotes the imaginary unit,  $\omega$  the angular frequency of the harmonic current,  $\sigma$  is the effective  
287 electrical conductivity,  $\epsilon_0$  is the electric permittivity of vacuum ( $8.854 \cdot 10^{-12}$  As/Vm),  $\epsilon_r$  is the relative electric  
288 permittivity,  $\mu_0$  is the magnetic permeability of vacuum ( $4\pi \cdot 10^{-7}$  Vs/Am) and  $\mu_r$  is the relative permeability.

289 The model was created by using a Single-Turn Coil domain feature and the governing equation of the  
290 induction coil under frequency-transient study analysis is given by:

$$I_{coil} = \int_{\partial\Omega} \mathbf{J} \cdot \mathbf{n} \quad (5)$$

292  
293  
294  
295

where  $I_{coil}$  denotes the flowing current of the coil.

Finally, the heating equation governed by the Fourier heat transfer equation is defined by:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \quad (6)$$

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297  
298

where  $\rho$  is the density,  $c_p$  is the specific heat capacity,  $k$  is the thermal conductivity,  $T$  is the temperature and  $Q$  is the energy generated in the asphalt mixture per unit volume and time.

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For the assessment of the influence of induction coil operational conditions on the induction heating potential of the inductive asphalt mortar, a finite element (FE) model was developed. The model makes use of one induction coil at a distance of 50 mm above the surface of the mortar sample, **Fig. 6.a**. The induction coil with a square cross-section of side 0.1 m was assumed. By imposing the alternative current to the coils, eddy current can be generated in the vicinity of the inductive asphalt mortar. It should be noted that the geometry of the induction coil has significant impact on the induction heating efficiency (29, 30). For this reason, the higher order tetrahedral elements were utilized to model the coil and the entire induction system, **Fig. 6.b**. In addition to the coil, the model consists of one layer of the inductive asphalt mortar with a thickness of 30 cm, one layer of ground sand soil underneath the mortar layer and air above the mortar layer. Normally the electro-thermal properties of inductive asphalt mixes are temperature dependent. However, for simplicity, the electro-thermal properties of the inductive asphalt mortar were assumed constant in the simulations.

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In order to make the asphalt mortar inductive, it was assumed that 6% of steel fibers was added into the asphalt mixture. The electrical and thermal conductivity of the inductive asphalt mortar were taken from the numerical analysis as well. Furthermore, in the following numerical simulations, the parameters of the relative permeability and heat capacity of the inductive mortar were assumed to be 1 and 920 J/(kg·K) respectively. Moreover, an ambient temperature of 20 °C was assumed to simulate the induction heating operation at normal environmental conditions. The duration of induction heating simulation was 120 seconds. The applied power voltage and the frequency of the alternating magnetic field were set to 550 V and 64 kHz for the simulations based on the experimental experience in the first part of this paper.

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## 4. Results

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### 4.1 Experimental results of asphalt mastics

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#### 4.1.1 *Micro-morphological images*

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The surface micro-morphology of asphalt mastic with iron powder is presented in **Fig. 7.a**. The different inductive asphalt mastics with different amounts of iron powder as described in Table 1 are investigated. The grey particles represent the mineral fillers and the brightest parts of the images are the iron powder. By comparing images 3 and 5 in **Fig. 7.b**, it is obvious that the inductive asphalt mastics without substituting the mineral filler - image 3 - appear to have a surface morphology with less dark space than asphalt mastics produced with substituting mineral filler with iron powder, image 5. The spacing among the filler-sized particles is reducing with increasing the amount of iron powder without substituting relative volumetric amount of mineral filler, images 1 to 3. Observation of inductive asphalt mastics surfaces with SEM images shows that the morphology of mastics after adding iron powder has a direct link with the concentration of filler-sized particles – iron powder and mineral fillers. It should be noted that the current micro-morphological results agree with the rheological results of inductive asphalt mastics which will be explained in the Frequency Sweep Test subsection.

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339

#### 4.1.2 *Frequency sweep test*

340 Before the frequency sweep tests, the stress sweep test was conducted from  $-10\text{ }^{\circ}\text{C}$  to  $60\text{ }^{\circ}\text{C}$  with a shear  
341 stress range from 0.01 to 10 Pa and at 1 Hz in order to identify the linear viscoelastic range (LVR). The LVR  
342 is characterized as the 10% stiffness reduction criterion and was used to filter the linear and non-linear  
343 viscoelastic region. Afterwards, the frequency sweep test was carried out over a temperature range from  $-10$   
344  $^{\circ}\text{C}$  to  $60\text{ }^{\circ}\text{C}$ . At a reference temperature of  $30\text{ }^{\circ}\text{C}$ , the master curves as given in **Fig. 8** show the rheological  
345 behavior for all the inductive asphalt mastics. **Fig. 8.a** is the complex modulus as a function of frequency with  
346 respect to different inductive asphalt-filler systems and **Fig. 8.b** is the corresponding phase angle as a  
347 function of frequency as well. The test stress sweep and frequency sweep were run on 8 mm parallel plates  
348 with a 2 mm gap for mastics at all the testing temperatures.

349 The asphalt mastic without adding iron powder is obviously much stiffer than the inductive mastics  
350 produced after replacing mineral filler with iron powder. From **Fig. 8.a** it can be seen that the complex  
351 modulus of mastic F100.P50 is significantly higher than the mastic F50.P50 which has the same amount of  
352 iron powder. Apart from the higher complex modulus, the inductive mastics have lower phase angle when  
353 iron powder is added without replacing the mineral filler, **Fig.8.b**. The reducing visco-elastic properties at  
354 higher concentrations of filler-sized particles and when particles are added without substitution are linked with  
355 the interaction between the fillers of different shape and surface characteristics. These phenomena can be  
356 explained by the fact that the surface of iron powder is slightly smoother than the other mineral fillers and  
357 thus is easily rolling under shear stresses when is added in the binder matrix by replacing mineral filler. Also,  
358 increasing the concentration of filler-sized particles leads to lower the spacing among the particles within the  
359 binder matrix and asphalt mastics with lower viscosity and higher stiffness are obtained. Consequently, the  
360 stiffening potential of the different filler-sized particles and the asphalt-filler processing methods result direct  
361 effects on the mastic's workability and subsequently on the durability of asphalt mixes.

#### 362 4.1.3 *Electrical and thermal properties*

363 The electrical resistivity of asphalt mastic decreases with increasing iron powder content with or without  
364 replacing an equivalent proportion of mineral filler, **Fig. 9**. In **Fig. 9.a**, a reduction of the electrical resistivity is  
365 observed when iron powder is mixed proportionally within the asphalt mastic by substituting mineral filler.  
366 Moreover, **Fig. 9.b** shows that the resistivity was also reduced after adding extra iron powder into the asphalt  
367 mastic matrix. The tendency of the electrical resistivity drop can be explained by the percolation threshold  
368 theory. The percolation threshold was reached when the shorter conductive pathways were formed by the  
369 higher amount of iron powder in the asphalt mastic. The inductive asphalt mastic F85.P15 represents the  
370 mastic at the percolation threshold position and adding more iron powder hardly reduces the electric  
371 resistivity further.

372 Additionally, the thermal conductivity of asphalt mastics produced, with and without substituting part of the  
373 mineral filler with iron powder, are presented in **Fig. 9**. It was found that the thermal conductivity of asphalt  
374 mastic increased after adding iron powder. The resulting increase is due to the thermal properties of iron  
375 which is added into the mastic. It is known that the thermal conductivity of iron powder is considerably higher  
376 than the conductivity of the other asphalt components. Hence the increase of the amount of iron powder  
377 leads to an increase of the effective thermal conductivity of the inductive mastic. This can be seen in **Fig.**  
378 **9.a&b** showing that the thermal conductivity of sample F85.P15, which represents the inductive asphalt  
379 mastic at the electrical percolation threshold, was  $0.56\text{ W/mK}$ . Also, the thermal conductivity of F85.P15 was  
380 higher than of pure asphalt mastic F100.P0 which was  $0.487\text{ W/mK}$ .

381 The asphalt mastics without replacing of mineral fillers with iron powder show a lower electrical resistivity  
382 than those developed after replacement. This observation can be explained by the fact that the filler-sized  
383 particles form a dense skeleton with very short spacing between the particles when extra iron powder is  
384 added in the asphalt mastic. Moreover, the produced inductive mastics without substitution of mineral filler-  
385 sized particles had a higher thermal conductivity. At higher filler-sized particles concentration, the interaction  
386 among the particles is increasing within the asphalt mastics. Thus, the spacing among the particles and the  
387 coating role of asphalt binder around the particles reduces having as consequence this thermal observation  
388 for the inductive asphalt mastics.

## 391 392 4.2 Experimental results of asphalt mortars

### 393 394 4.2.1 *Electrical and thermal properties*

395  
396 The change of the electrical resistivity of an asphalt mortar with steel fibers, but without iron powder is shown  
397 in **Fig. 10.a**. The conductive paths formed by steel fibers develop and lead to a gradual decrease of the  
398 resistivity above 2% volume of fibers. It is clear that the increase of the volume of steel fibers reduces the  
399 resistivity or increases the electrical conductivity of mortars. The optimum steel fibers content reached when  
400 no longer increases the electrical conductivity by adding more than 6.4% of steel fibers. For adding iron  
401 powder in the mortars with constant steel fibers content, it was selected asphalt mortar with 4% of steel fibers  
402 as a inductive mortar with amount of steel fibers beyond the percolation threshold.

403 The combination of steel fibers and iron powder further reduces considerably the electrical resistivity of the  
404 asphalt mortar, **Fig. 10.b**. It can be seen that, by choosing asphalt mortar with 4% of steel fibers and adding  
405 the iron powder stepwise in parallel with the reduction of mineral filler, the replacement of mineral filler with  
406 iron powder decreases the electrical resistivity of the asphalt mortar further. The optimum combination of  
407 particles in the asphalt mortar is 4% of steel fibers and 15% of iron powder. The amount of iron powder  
408 required to obtain the optimum combination of particles and according to the percolation threshold theory the  
409 shorter conductive pathway coincides with the previous observations at the mastic level. This volume  
410 combination of steel fiber and iron powder will be used for the further steps of this research.

411 For composite materials such as asphalt mixes, the effective properties can be determined by the  
412 proportion, the dispersion and the properties of individual components in the final material. By increasing the  
413 proportion of a component in the mix, the thermal conductivity of the final mix can be increased or decreased  
414 depending on the type and the nature of the component. In case of adding steel fibers, it is observed that the  
415 effective thermal conductivity of asphalt mortar increases with the additions of fibers, **Fig. 11**. Due to the fact  
416 that the thermal conductivity of steel fiber is quite high, when the volumetric part of steel fibers into the  
417 asphalt mortar is increased or decreased, the effective conductivity of the whole mix will increase or decrease  
418 respectively. The increase of thermal conductivity is slightly higher in the case of asphalt mortars mixed with  
419 both iron powder and steel fibers.

### 420 421 4.2.2 *Direct tensile strength and fatigue performance*

422  
423 The direct tensile strength and fatigue tests provide crucial information about the impact of particles on the  
424 mechanical performance of the inductive asphalt mortar. The asphalt mortar is the first decentralized system  
425 of an asphalt mix and represents the matrix of the mix between the aggregates. This implies that the  
426 mechanical behaviour of mortar has a direct effect on the behaviour of mixes on pavements. The typical  
427 stress-strain curves at low temperatures (-10°C) and at different displacement rates are presented in **Fig. 12**.  
428 It is obvious that the amount of steel fibres influences the maximum tensile stress. The tensile strength of the  
429 mortar increases with increasing fibre content. Therefore, the reinforcing effect of fibres on the asphalt mortar  
430 is apparent in **Fig. 12.c**, where the average values of the maximum tensile stresses are presented.

431 The effect on brittleness and ductility of the inductive asphalt mortar can be observed in **Fig. 12**. At high  
432 displacement rates, all samples show brittle response. More ductility can be observed for lower fiber contents  
433 and lower displacement rate. Particularly, the replacement of a part of mineral filler with iron powder, it does  
434 not influence significantly on the tensile strength of the asphalt mortar and the reinforcing effect of fibers.

435 In order to study the fatigue response of mortars with different combinations of inductive particles, a cyclic  
436 sinusoidal load is utilized. The magnitude of the loading is defined as the 40% of the ultimate tensile strength  
437 (0.3 kN). The loading frequency was 5 Hz and all the tests were carried out at -10 °C.

438 It can be observed that all asphalt mortar samples show the tertiary phase of deformation after certain  
439 loading time, **Fig. 13.a&b**. Particularly, by increasing the amount of steel fibers within mortar from 0% to 4%,  
440 the tertiary phase is significantly delayed and the fatigue life increases. Moreover, the fatigue life is extended

441 when steel fibers were added from 4% to 6% within the asphalt mortar. It can be seen that the asphalt mortar  
 442 with 15 % of iron powder appear slightly higher fatigue life than the one without iron powder, **Fig. 13.c**.

443

#### 444 *4.2.3 Induction heating performance*

445

446 In order to investigate the induction heating efficiency of the inductive asphalt mortar, at ambient temperature  
 447 (20 °C), the test samples were heated for 120 seconds by the induction unit. The test samples were mixed  
 448 with different volumetric combinations of steel fibers and iron powder. **Fig. 14** presents the average  
 449 temperature at the top surface of samples at 120 seconds induction heating. It can be observed that the  
 450 maximum surface temperature is related to the volume of steel fibers added in the asphalt mortar. The higher  
 451 amount of fibers in the mortar sample led to the higher surface temperature and hence the higher induction  
 452 heating efficiency of mortar. However, the increasing tendency of induction heating efficiency is not linear.  
 453 For example, after 6% of fibers added in the mortar, the tendency of increasing temperature is not significant  
 454 and it is stabilized. It means that mortars achieve the induction heating saturation limit where all the  
 455 conductive paths are linked.

456 Similar observation can be found for the samples mixed with both iron powder and steel fibers. It can be  
 457 seen that the induction heating efficiency can be enhanced by combination of iron powder and steel fibers  
 458 into the asphalt mortar. The average surface temperature of the samples with 15% iron powder is higher than  
 459 the samples without powder.

460

#### 461 *4.2.4 Induction healing performance*

462

463 The induction healing efficiency of asphalt mortar with steel fibers is presented in **Fig. 15.a**. The cracks were  
 464 healed by induction heating. However, after the first healing cycle, the strength was recovered by 60% of its  
 465 original strength. This phenomenon can be explained by the loss of reinforcing effect of steel fibers in mortar  
 466 (17). Apart from the induction healing of mortar, the use of steel fibers offers a reinforcing matrix with a  
 467 network of random oriented fibers. However, when mortar is fractured, the interconnection among the fibers  
 468 at the cracked surfaces is lost and mechanical performance of inductive mortar is as a material without fibers.  
 469 In the second and third cycle, the strength recovery remained approximately constant. In the fourth cycle,  
 470 material lost its strength completely. After several fracture - healing cycles, the cracked surfaces of fractured  
 471 mortars were covered mostly by asphalt binder without steel fibers. As a result, the diffusion of binder from  
 472 the one side of surface to the other was prohibited and subsequently the closure of crack of asphalt mortar.  
 473 The fracture - healing process was continued successively in six cycles. Similar to the case of mortar mixed  
 474 with fibers, the combination of steel fibers and iron powder can provide the same induction healing capacity  
 475 to mortar, **Fig. 15.b**.

476

### 477 *4.3 Numerical results of asphalt mortars*

478

#### 479 *4.3.1 Numerical analysis of effective material properties*

480

481 For the determination of electro-thermal properties of the inductive asphalt mortar, it is necessary to predefine  
 482 the properties of individual components in the asphalt mortar. Therefore, in this investigation, the magnitudes  
 483 of the electrical and thermal conductivity of the bitumen, mineral filler and sand were assumed to be  $9 \cdot 10^{-5}$   
 484 S/m and 0.5 W/(m·K) respectively and for steel fiber  $20 \cdot 10^3$  S/m and 16 W/(m·k) were assumed (25, 26). The  
 485 3D images of the asphalt mortars with different steel fibers contents are presented in **Fig. 16** and their  
 486 effective electrical and thermal conductivities are determined numerically and given in **Fig. 17**.

487 The results in **Fig. 17** indicate that the electrical conductivity of the asphalt mortar increased with  
 488 increasing the content of steel fiber. As it can be noticed, the electrical conductivity of the asphalt mortar  
 489 increases rapidly when the volume fraction of the steel fiber is close to 6%. The reason of this dramatic  
 490 increase of the electrical conductivity can be explained by the percolation threshold theory. The percolation  
 491 threshold is reached when the shorter conductive pathways are formed by the higher amount of steel fibers in

492 the asphalt mortar. Similarly, it can be observed that, with the stepwise increase of steel fibers in the asphalt  
 493 mortar, the effective thermal conductivity of the inductive asphalt mortar is increased from 0.71 W/(m·K) to  
 494 1.58 W/(m·K). This happened because the thermal conductivity of steel fibers is higher than the other  
 495 components in the asphalt mortar.

496 According to the current numerical analysis, the improvement of effective electrical and thermal  
 497 conductivity is dependent on the proportion of steel fibers in the asphalt mortar. Moreover, it is well known  
 498 that it is difficult to obtain experimentally precise conductivity results from asphalt mixes (28). Therefore, this  
 499 method of numerical analysis of asphalt mortar properties could be proved an effective tool to determine the  
 500 electro-thermal characteristics of inductive asphalt mixes. Subsequently, understanding the conductivity  
 501 mechanism is also another advantage of this numerical technique where the transformation phenomenon of  
 502 asphalt mix, from insulator to conductor, can be quantified by identifying the percolation threshold limit.  
 503

#### 504 4.3.2 Numerical analysis of induction heating

##### 506 *Effect of Material Properties*

507 The numerical simulations for the one coil system were carried out first. The distribution of magnetic flux  
 508 density and temperature on the inductive asphalt mortar are shown in **Fig. 18**. The influence of the electrical  
 509 conductivity on the temperature distribution within the cross-section of the asphalt mortars is shown in **Fig.**  
 510 **19**. It should be noted that the asphalt mortar with 100 S/m of electrical conductivity corresponds to the  
 511 response of the asphalt mortar mixed with 6% of steel fibers. Hence, the asphalt mortar with 1 S/m of  
 512 electrical conductivity represents the mortar mixed with a lower amount of steel fibers.

513 It can be observed in **Fig. 19** that, after 120 seconds of induction heating, for the case of the asphalt  
 514 mortar with 100 S/m of electrical conductivity, the surface temperature is higher than with 1 S/m (lower  
 515 amount of steel fibers). This finding supports the observations made by previous researches (15), where the  
 516 induction heating efficiency appears to be proportional to the volume of the inductive particles added in the  
 517 asphalt mixes.

518 The amount of steel fibers can also influence the thermal gradient inside the asphalt mortar, **Fig. 19**. For  
 519 example, for the case of asphalt mortar with 100 S/m of electrical conductivity, the temperature decreases  
 520 faster inside the mortar, than the case 1 S/m. This thermal gradient difference is caused by the skin effect.  
 521 When a inductive asphalt mortar has a high electrical conductivity, the alternating magnetic field induces  
 522 electric currents which are concentrated on the surface of the inductive asphalt mortar. The high  
 523 concentration of the electric currents leads to a higher heat generation at the surface of the inductive asphalt  
 524 mortar. Therefore the asphalt mortar with higher electrical conductivity (e.g., 100 S/m) has a higher  
 525 temperature at the surface but a lower temperature inside the material.

526 In **Fig. 20**, the effect of thermal conductivity and heat capacity of inductive asphalt mortars is also  
 527 presented. The parametric analyses are done for inductive asphalt mortar with two different heat capacities  
 528 (e.g., 875 and 925 J/(kg·K) ), four different thermal conductivities (e.g., 0.5, 0.7, 0.9, 1.1 W/(m·K)), while the  
 529 electrical conductivity of the compared mortars is constant (100 S/m). By comparing to **Fig. 19**, it can be  
 530 concluded that the impact of the thermal properties of the asphalt mortar on the temperature distribution is  
 531 not of the same importance with the effect of electrical conductivity.  
 532

##### 533 *Effect of Operational Parameters*

534 The numerical results in **Fig. 21** show that the distance between the induction coil and the inductive mortar  
 535 can influence significantly the heat generation in the inductive asphalt mortar. By increasing the coil distance  
 536 from 50 mm to 100 mm to the mortar surface, it leads to 50% reduction of the temperature at the surface of  
 537 the asphalt mortar. This means that for surface induction heating coil closer to the surface is more efficient  
 538 one at larger distance from the surface of the asphalt mortar. Moreover, the tendency is similar for the  
 539 materials with different electrical conductivity values.

540 The power and the frequency of the alternating magnetic field of the induction machine are two important  
 541 operational parameters that can influence significantly the induction heating efficiency of the inductive asphalt  
 542 mortar. **Fig. 21** shows the comparison of the effect of the power and the frequency of the induction coil on the

543 temperature distribution inside the inductive asphalt mortar. It can be observed that, at the same frequency  
 544 (e.g., 30 kHz), higher machine power results in higher temperatures generated in the material over the whole  
 545 height.

546 On the other hand, the frequency of the magnetic field is another important operation parameter. It can be  
 547 seen that, at constant voltage (e.g., 550 V), the lower frequency of 30 kHz leads to higher maximum surface  
 548 temperature than the higher frequency of 64 kHz. The distribution of the temperature within the cross-section  
 549 of the inductive asphalt mortar shows the same tendency for the both cases.  
 550

## 551 5. Conclusions

552  
 553 The findings of this research were within the efforts to enhance the induction heating of asphalt mixes  
 554 preparing simultaneously materials with improved mechanical performance during their service. Also, the  
 555 valuable findings of this research show that it is possible to optimize the necessary tools and equipment  
 556 needed for the implementation of the induction technology for heating and subsequently healing asphalt  
 557 pavements. Based on the results presented in this paper, the following conclusions can be made:  
 558

- 559 • The increase of inductive particles contributes to the enhancement of the electrical and thermal  
 560 conductivity of asphalt mastic and mortar as well. The utilization of steel fibers has significant  
 561 improvement on the electrical conductivity of asphalt mortar than the one with iron powder. Moreover,  
 562 combining steel fibers and iron powder within the mortars, the thermal conductivity is slightly higher  
 563 than using only steel fibers as inductive particles.
- 564 • When steel fibers are added in the asphalt mortar, the tensile strength is improved and the fatigue life  
 565 is extended. Similar mechanical response is obvious also by combining iron powder and steel fibers.
- 566 • The induction heating efficiency is increased when iron powder and steel fibers are added  
 567 independently to a certain limit, where the temperature does not increase anymore. Apart from the  
 568 highest induction heating efficiency, asphalt mortars have similar induction healing capacity with  
 569 mortars with steel fibers when iron powder is mixed.
- 570 • Finally, the application of numerical simulations to evaluate the effective properties of inductive  
 571 asphalt mixes and the different operational conditions of induction heating is proved to be a very  
 572 effective tool, capable to perform analysis without conducting time consuming and costly  
 573 experiments. The 3D induction heating numerical model enables to calibrate the model parameters to  
 574 perform more realistic heating simulations for asphalt concrete mixes.  
 575

## 576 Acknowledgements

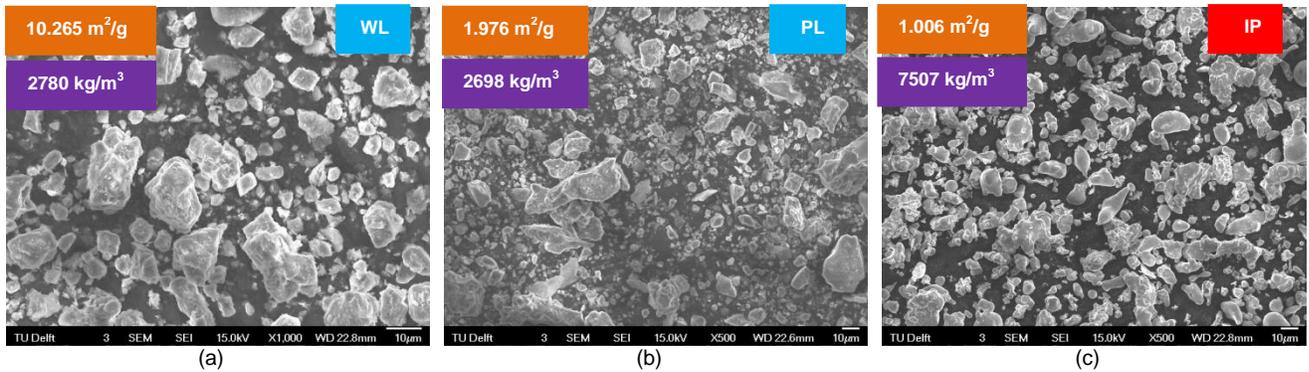
577  
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 580 thermal testing.  
 581

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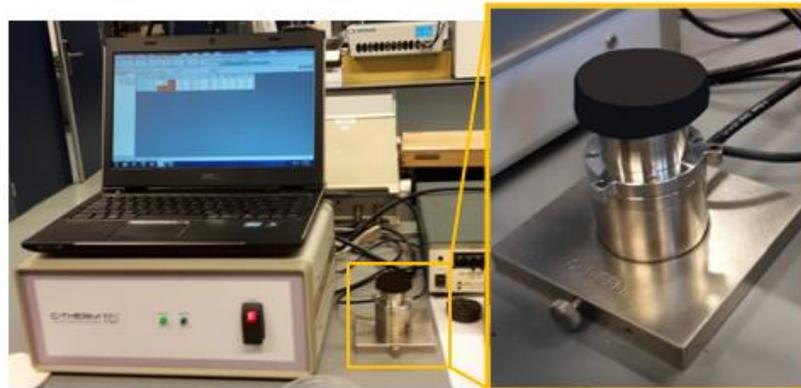
692 **FIGURE 1** High magnification SEM SEI images of filler-sized particles with their physical properties; (a) WL,  
 693 (b) PL and (c) IP  
 694

695 **TABLE 1** Composition of inductive asphalt mastics  
 696

| Type of mastic | Density of mastic (gr/m <sup>3</sup> ) | Mineral filler WL (gr) | Mineral filler PL (gr) | Iron powder IP (gr) |
|----------------|--|------------------------|------------------------|---------------------|
| F100.P0        | 1.594                                  | 50.40                  | 7.10                   | 0.00                |
| F95.P5         | 1.646                                  | 47.88                  | 6.75                   | 7.79                |
| F90.P10        | 1.683                                  | 45.36                  | 6.39                   | 15.58               |
| F85.P15        | 1.730                                  | 42.84                  | 6.04                   | 23.37               |
| F80.P10        | 1.844                                  | 40.32                  | 5.68                   | 31.16               |
| F75.P25        | 1.957                                  | 37.80                  | 5.33                   | 38.95               |
| F50.P50        | 2.243                                  | 25.20                  | 3.55                   | 77.90               |
| F25.P75        | 2.455                                  | 12.60                  | 1.78                   | 116.85              |
| F0.P100        | 2.796                                  | 0.00                   | 0.00                   | 155.80              |
| F100.P25       | 2.361                                  | 50.40                  | 7.10                   | 38.95               |

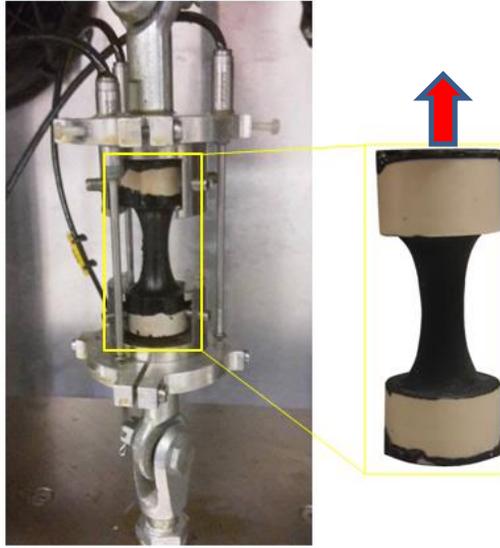
MA: asphalt mastic, F: mineral filler, P: iron powder, bitumen (gr): 42.5

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**FIGURE 2** TCI analyzer and specimen during thermal measurement



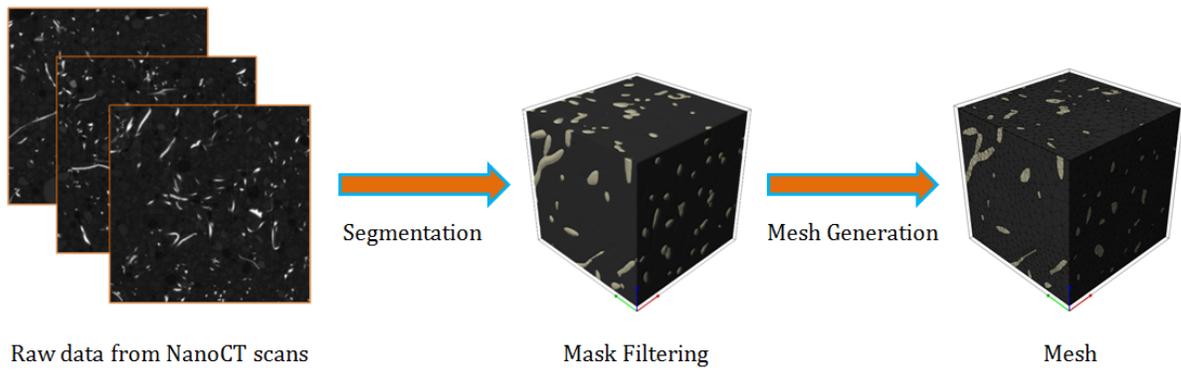
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**FIGURE 3** The frame and asphalt mortar specimen



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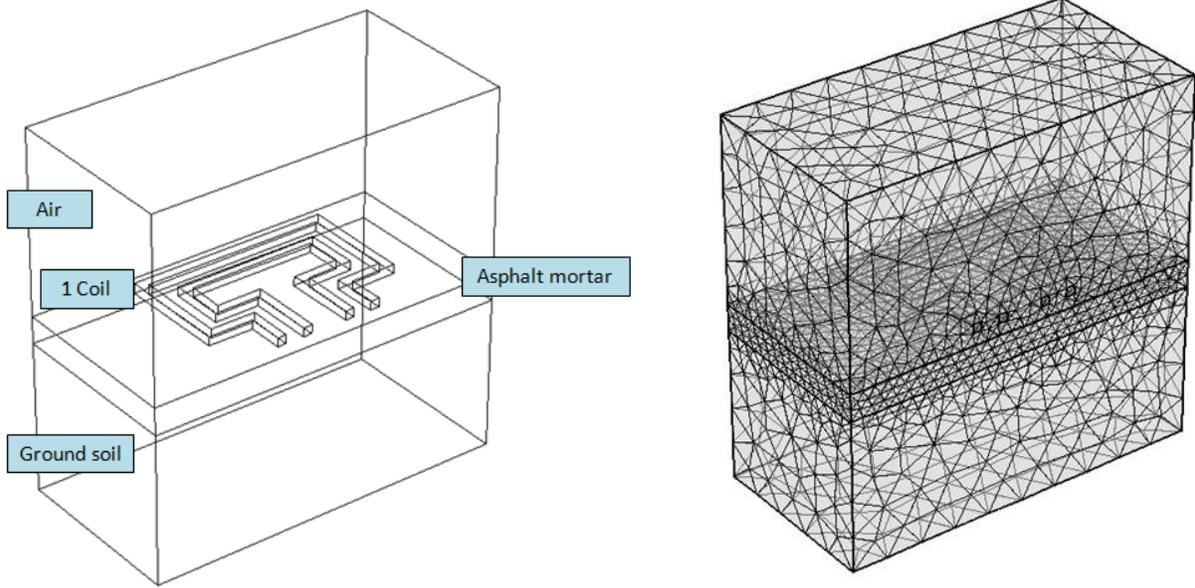
**FIGURE 4** Induction heating machine used at laboratory



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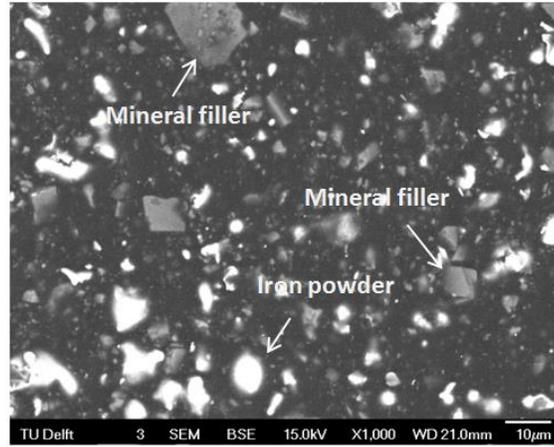
**FIGURE 5** Overview of 3D image data post processing

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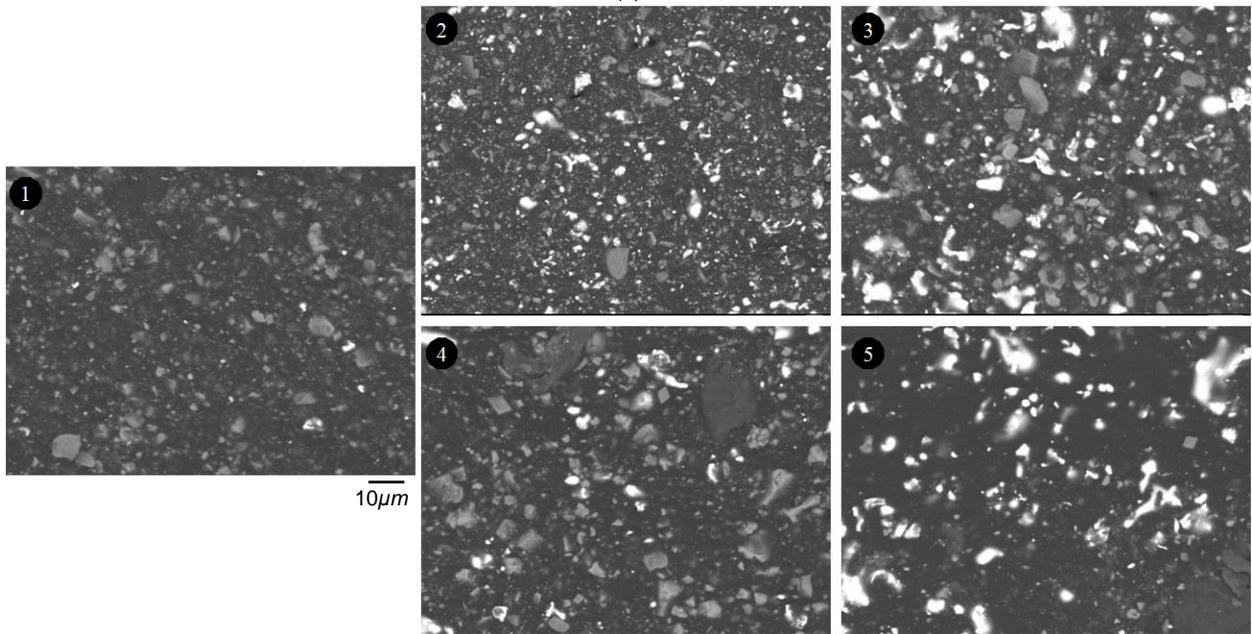


(a) (b)  
**FIGURE 6** Schematic of (a) one coil and (b)the relative mesh refinements

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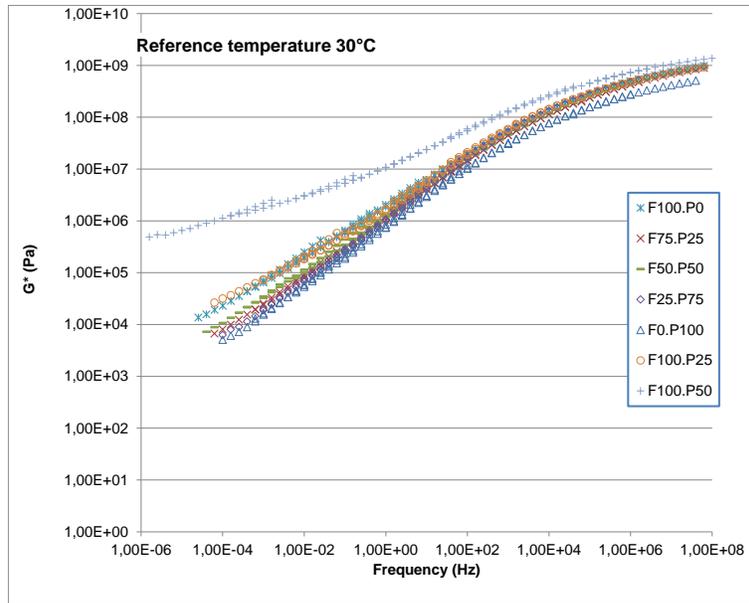


(a)

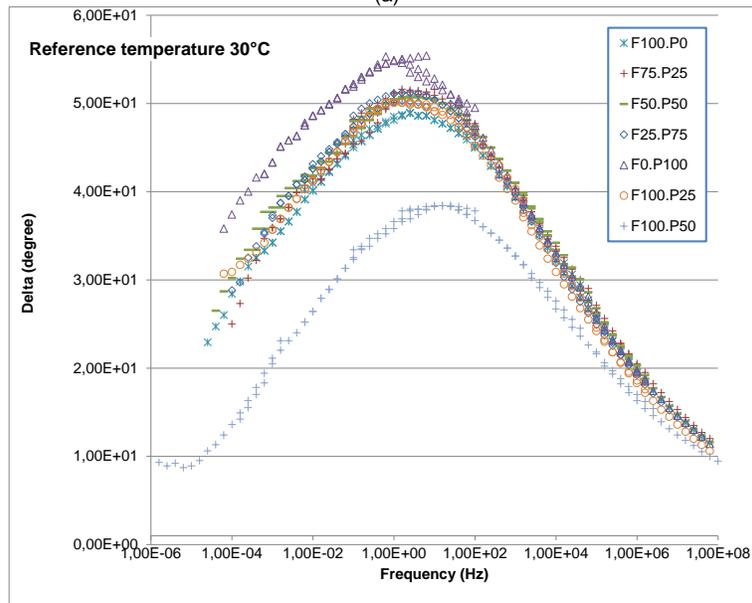


(b)

727 **FIGURE 7** SEM BSE (a) image of a inductive asphalt mastics with iron powder and (b) images of inductive  
 728 asphalt mastics demonstrating the influence of replacing mineral filler with iron powder on the micro-  
 729 morphology: (1) F100.P0, (2) F100.P25, (3) F100.P50, (4) F75.P25 and (5) F50.P50  
 730

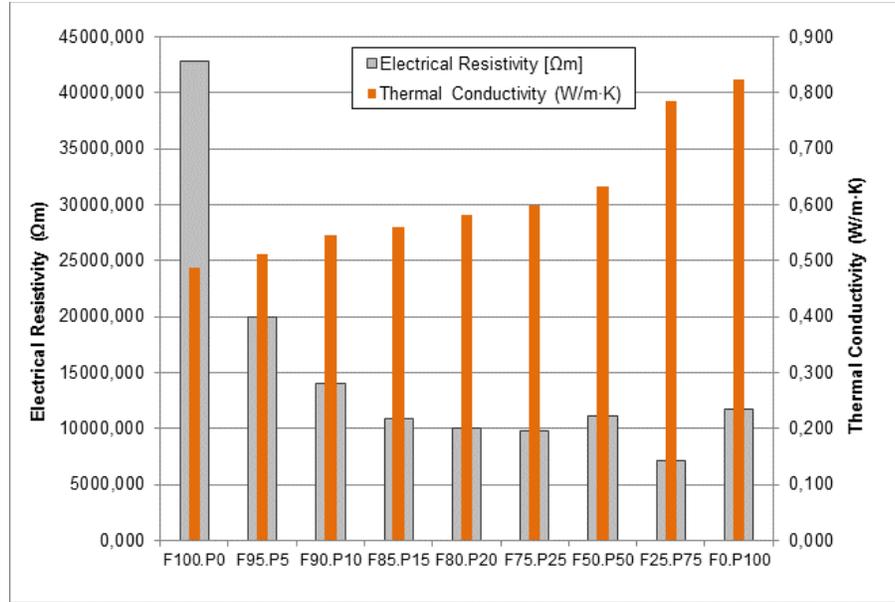


(a)

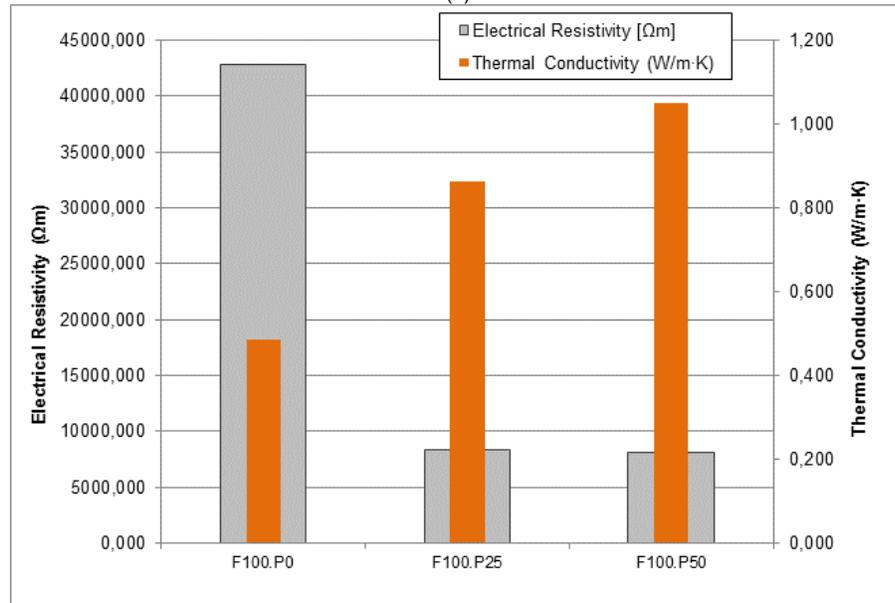


(b)

731 **FIGURE 8** (a) Complex modulus and (b) phase angle master-curves for asphalt mastics produced with and  
 732 without replacing part of mineral filler with iron powder  
 733

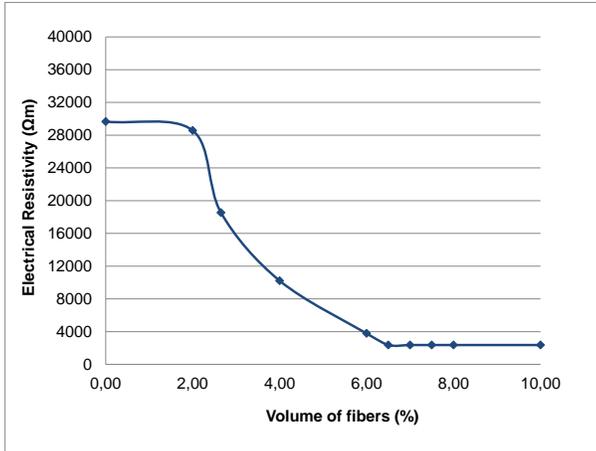


(a)

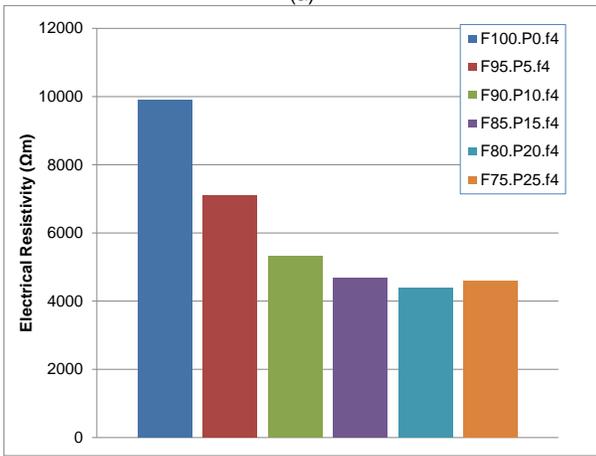


(b)

734 **FIGURE 9** Effect of the volume content of iron powder on the electrical resistivity and thermal conductivity of  
 735 asphalt mastics (a) after replacing mineral filler with iron powder and (b) without replacing mineral filler with  
 736 iron powder at 20 °C  
 737  
 738

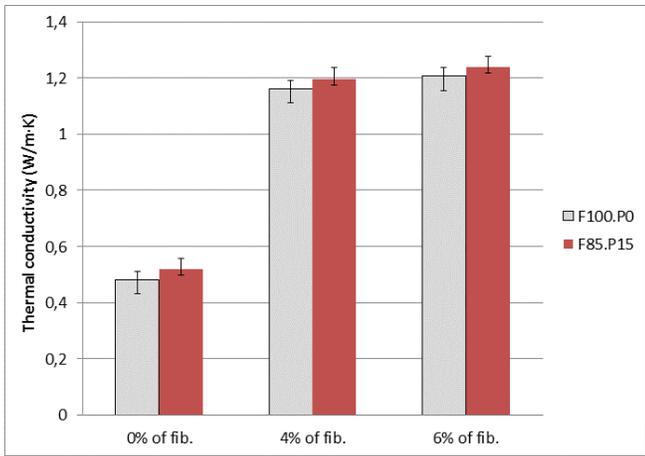


(a)



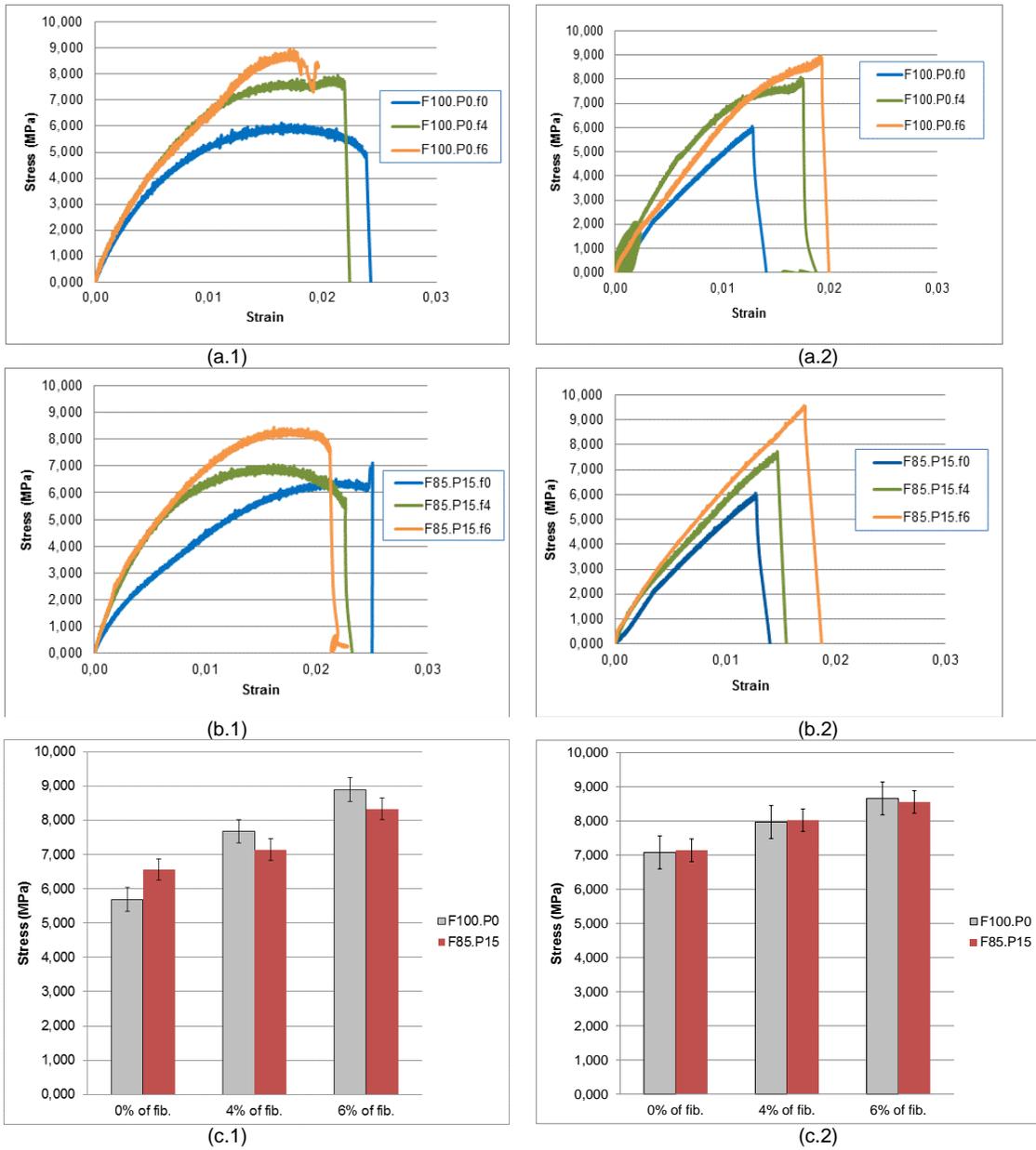
(b)

739 **FIGURE 10** Effect of (a) the volume content of steel fibers and of (b) iron powder after substituting mineral  
740 filler with iron on the electrical resistivity of asphalt mortars at 20 °C  
741

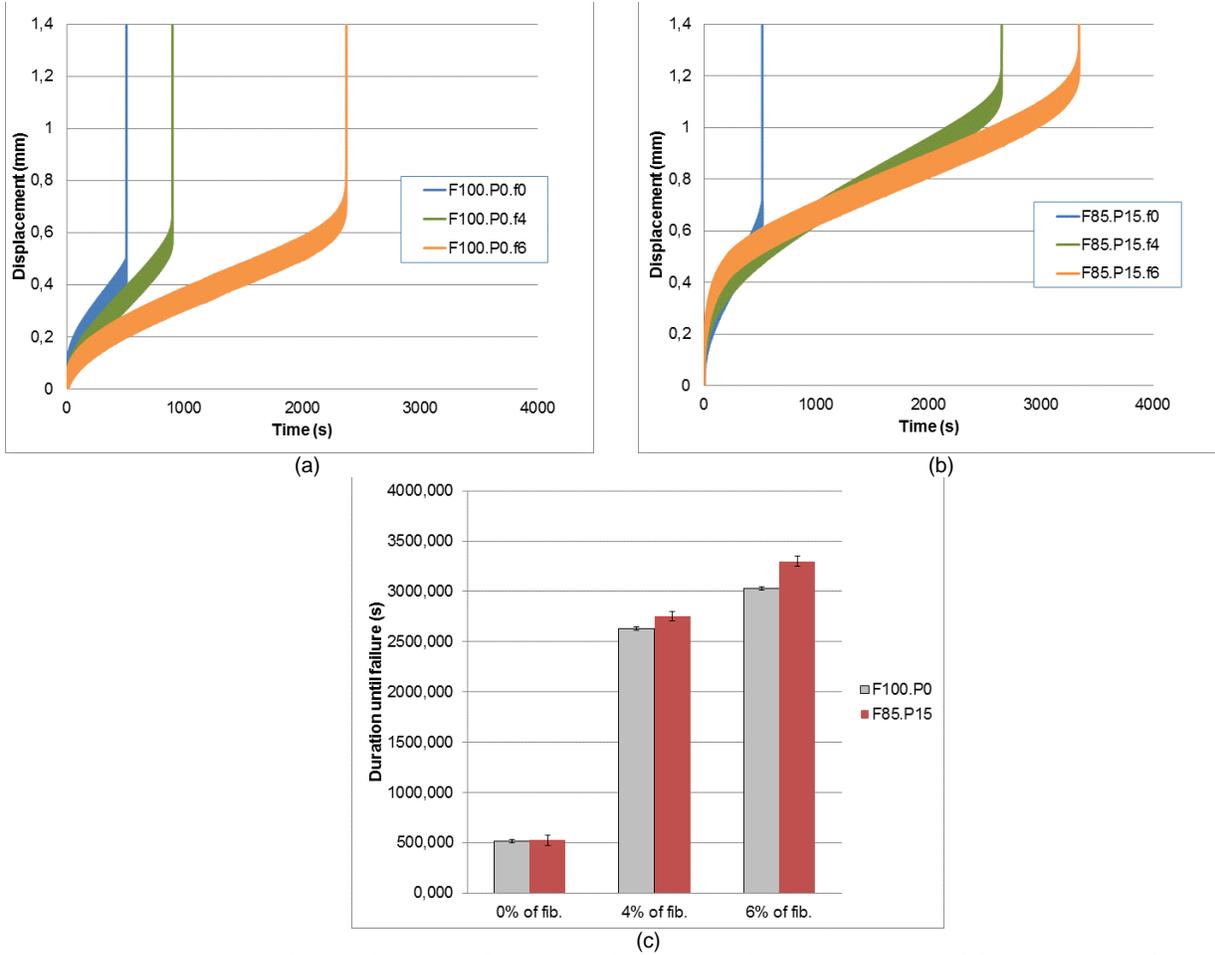


742 **FIGURE 11** Effect of the volume content of steel fibers on the thermal properties of asphalt mortar with and  
743 without substituting mineral filler with iron powder at 20 °C  
744

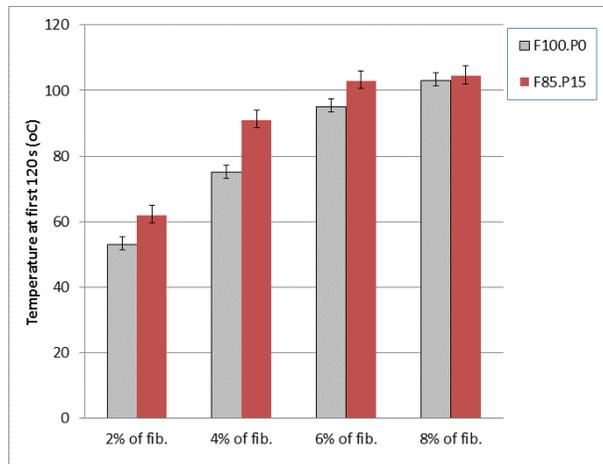
745



746 **FIGURE 12** The total graphs with the tensile strength of asphalt mortars: displacement rate (c.1) 0.0275  
747 mm/s and (c.2) 0.05 mm/s at -10 °C  
748

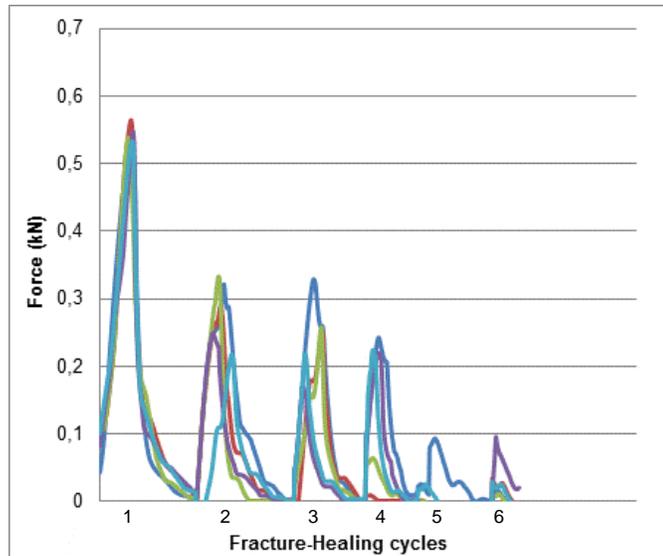


749 **FIGURE 13** Influence of steel fibres on fatigue performance of asphalt mortars (a) without and (b) with iron  
 750 powder, and (c) the total graph with the fatigue life of different mortars at -10 °C  
 751

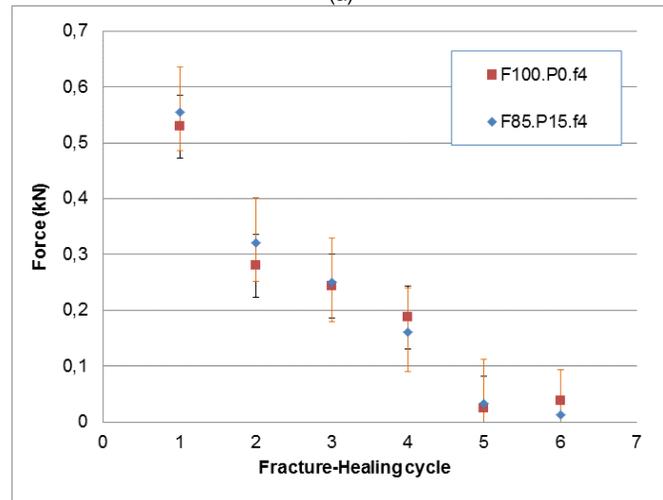


752 **FIGURE 14** Temperature reached after 120 seconds induction heating for asphalt mortar with constant  
 753 volume of steel fibers and different volumes of iron powder  
 754

755

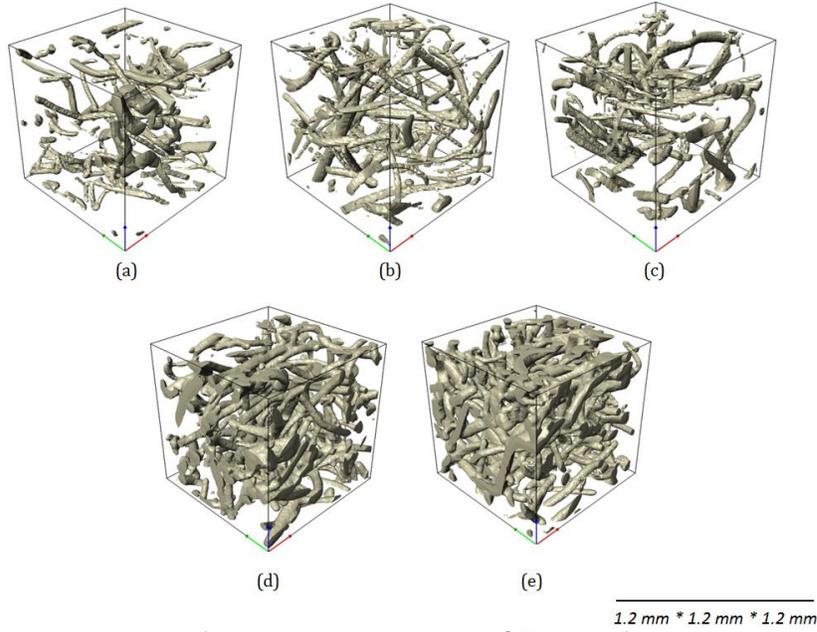


(a)

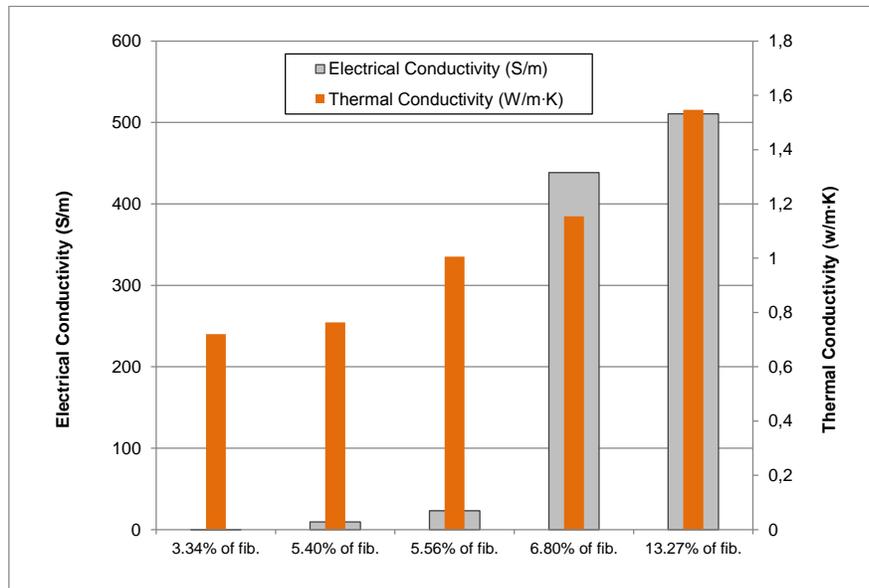


(b)

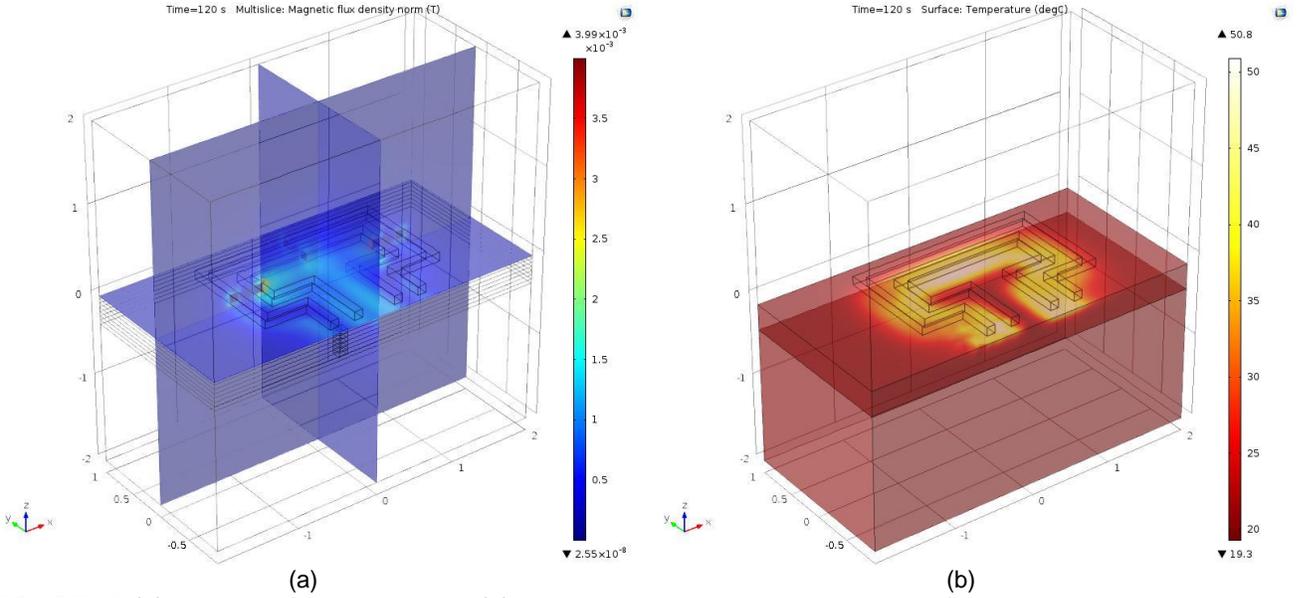
756 **FIGURE 15** (a) Stress-strain curves for asphalt mortar containing 4% of steel fibers and (b) strength  
757 comparison for two types of asphalt mortars at -10 °C  
758



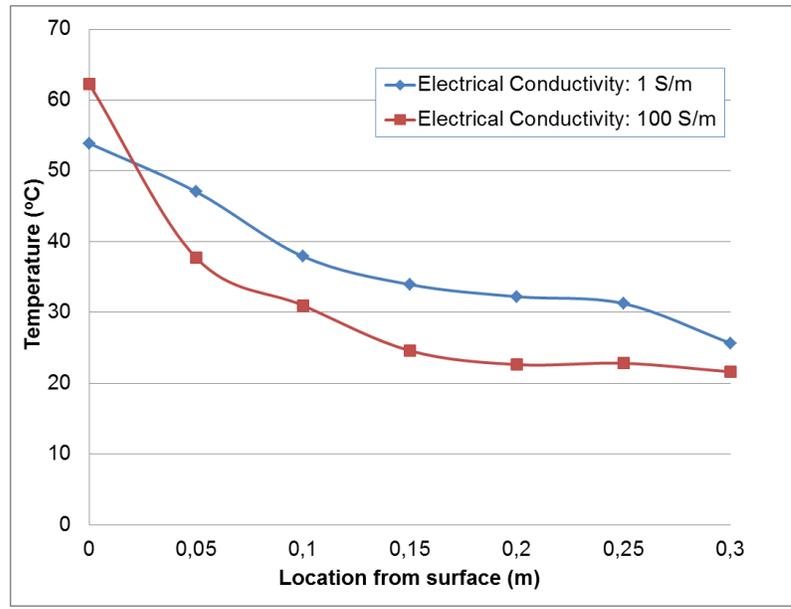
759 **FIGURE 16** Reconstructed images after segmenting the NanoCT-scans for the inductive asphalt mortars with  
760 different steel fibers content; (a) 3.4 %, (b) 4.7 %, (c) 5.2 %, (d) 6.8 % and (e) 13.3 % of steel fibers  
761



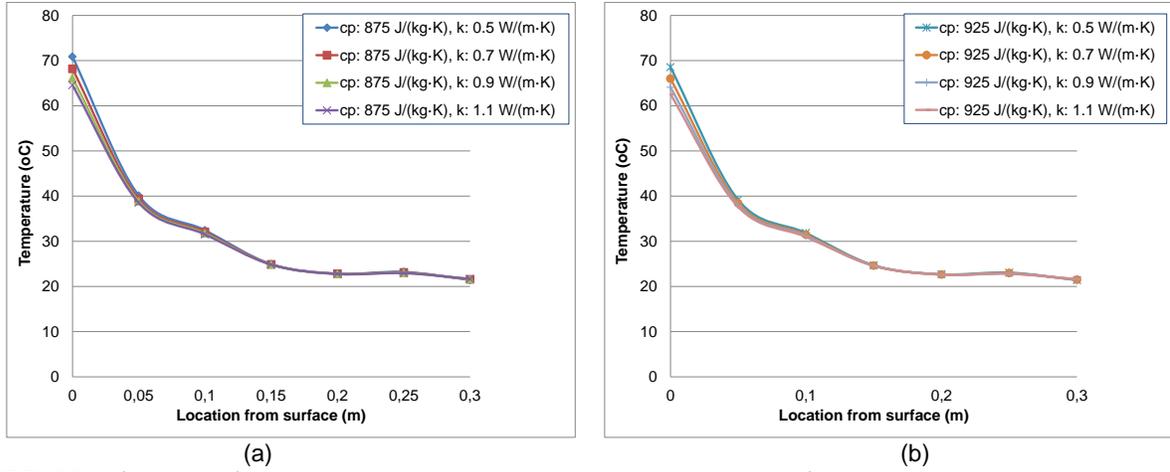
762 **FIGURE 17** Numerically determined effective (a) electrical and (b) thermal conductivity of different asphalt  
763 mortars  
764  
765  
766



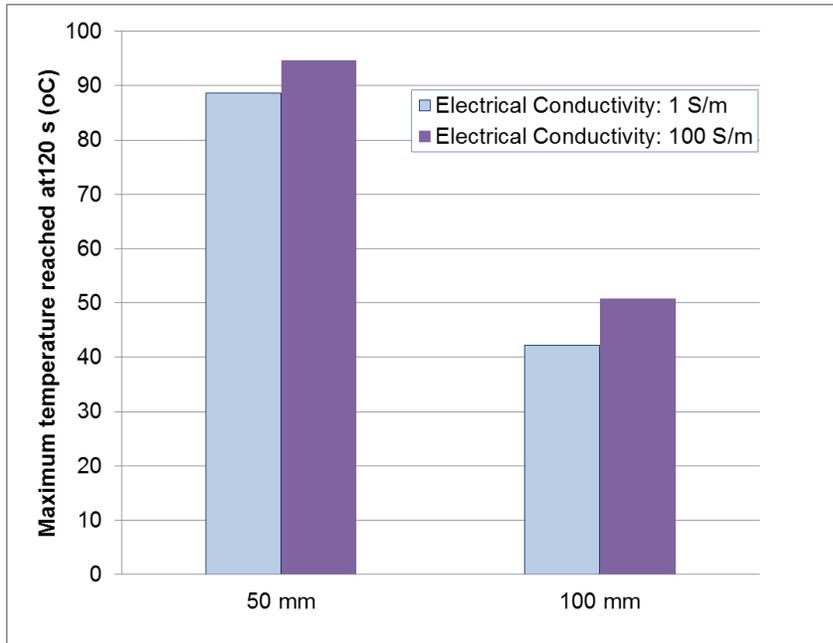
767 **FIGURE 18** (a) Magnetic flux density and (b) temperature distribution at the end of induction heating  
768



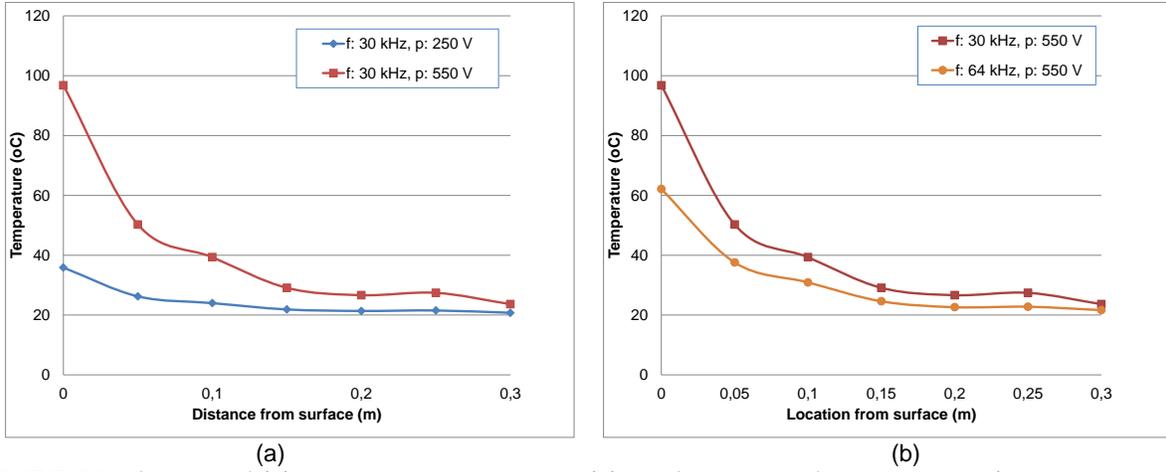
769 **FIGURE 19** Influence of the electrical conductivity of the inductive asphalt mortars on temperature distribution  
770 (induction time 120s)  
771  
772  
773



774 **FIGURE 20** Influence of the thermal conductivity and heat capacity of the inductive asphalt mortars on  
775 temperature distribution (electrical conductivity 100 S/m, induction time 120s)  
776



777 **FIGURE 21** Maximum temperature generated by the single coil system at the different electrical  
778 conductivities at the different coil distances to the inductive asphalt mortar  
779  
780



781 **FIGURE 22** Influence of (a) the supplied power and (b) the frequency of induction coil (electrical conductivity  
 782 100 S/m, induction time 120s)